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Technical Report No. 552

A TEXT ANALYSIS OF TWO PRE-SECONDARY SCHOOL SCIENCE ACTIVITIES

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Abstract

Two typical science activities found in textbooks for elementary and middle school students were analyzed to determine the quality of the written text and the integrity of the science represented in the activity. Each activity was performed and critiqued from a number of perspectives. The framework used to compare and contrast these activities is recommended as useful for curriculum designers, textbook selection committees, and classroom teachers.

A TEXT ANALYSIS OF TWO PRE-SECONDARY SCHOOL SCIENCE ACTIVITIES

Almost all chapters in science textbooks contain at least one section with a "hands-on" activity. These sections, usually no more than a page or two in length, lead the reader to believe that the activities are related to the science topic in the chapter, and that they can be performed by students. The titles of the activities vary from publisher to publisher and from grade level to grade level. They have titles such as: Testing Disinfectants, Now Try This, Finding Out, How Are Some Weather Predictions Made?, Temperature and Chemical Reactions, and The Water Cycle in an Ecosystem. Sometimes the title reflects a question to be answered during the activity (How Are Some Weather Predictions Made?), indicates a science topic to be investigated (The Water Cycle in an Ecosystem), or gives a sign that what follows will be hands-on (Now Try This).

Most publishers provide teacher materials to accompany the activities, such as the so-called Activity-Centered Program Guide (Wynn & Finsand, 1984), which accompanies one of the science curriculum packages reviewed below. This guide is 18 pages long and is a description of (among other topics) laboratory design and equipment, laboratory techniques, equipment, supply lists, and safety in the laboratory. This information is not reproduced in the students' textbooks, however. In addition to these materials, teachers may also use science trade books that contain an abundance of science activities.

Our purpose in this report is to review and critique two activities taken from elementary and middle school science textbooks. We analyze the science involved in these activities as well as the segment of text and diagrams from the students' textbook that provides instruction for the students. Our observations are presented in a framework that we think will be useful to curriculum designers and adoption committees.

We are working from a belief system that suggests that the design of these activities is crucial to the cognition (elaborating, expanding, clarifying, solidifying, synthesizing, applying, and predicting) that takes place as a result of doing or attempting to do them. Thus, it seems important that science activity tasks and the sequence of the tasks be strategically planned and implemented.

Method

We collected about 50 science activities from 10 different basal program publishing houses and about 12 different "science activity" trade books by a variety of authors and publishers. Individually and as a team, we read and analyzed many of these activities in an effort to understand what they meant, their design, the rationale for the design, and what students might think of them.

Although we tried to be objective with our analysis, we brought with us perspectives from a number of sources. One of these sources was a set of guidelines developed for similar purposes but with children's expository textbook materials (see Anderson & Armbruster, 1985, for the results of those analyses). While our main objective, initially, was to understand the kinds of problems that students have when they read and perform science activities and not to develop a set of guidelines, we felt that our struggle to develop an objective approach to this analysis may be helpful. These guidelines (or framework) may benefit curriculum developers, publishers, and textbook adoption committees.

In addition to the "guidelines-driven analysis," we performed several of the activities in a science education laboratory. We simulated what we thought the teacher and students would be doing as they read and performed each activity. During this simulation we maintained a record of events that served as a source of information for the critiques that follow.

We assumed that the activities were designed so that students could read and perform them individually, in pairs, or, perhaps, in small groups, with only occasional help from the teacher. We thought that this assumption was reasonable because the activities were incorporated into the students' textbooks as if the students were to read and interact with them. In addition, we assumed that prior to the performance of the activity, the teacher would have collected and organized the equipment listed in the Materials section of the activity.

We term the two activities critiqued in this report the "aquarium activity" and the "flask activity." These activities were chosen because they address the same general science topic: an explanation of or use of principles associated with the water cycle; and water cycle activities are found in most, if not all, science curriculum packages. Also, children's views about the water cycle has been a topic in its own right as a rich area for investigating children's scientific misconceptions (Bar, 1989) and cognitive development (Piaget, 1972; Piaget & Inhelder, 1969). Another compelling reason for choosing this topic is that children often experience phenomena related to the water cycle.

While the two activities are similar in topic, they use very different procedures. In the flask model, salt water is boiled in a flask and the resulting steam is "tubed" into a beaker that collects the condensed water droplets. A hot plate is the power source (Wynn & Finsand, 1984). In the aquarium model (Trowbridge, Sund, Adams, Hackett, & Moyer, 1983), "muddy" water in the bottom of the aquarium evaporates and later condenses on a plastic sheet that covers the aquarium. Water droplets from the plastic sheet fall into a small jar which serves as a collector. The sun powers these processes.

In the following sections, we present our analysis and a critique of each of these activities and describe a framework for organizing and summarizing the results of the analysis.

Critique of the Flask Activity

The flask activity was taken from a chapter about oceanography in a middle school earth science textbook (Wynn & Finsand, 1984). The description of the activity contains a title and three paragraphs. The first paragraph is subtitled *Materials*. The other paragraphs did not have subtitles but consisted of procedural steps and questions. There are 240 words in the description and a diagram of how to assemble the equipment needed for the activity. What follows is our critique of each step in the description. We have added sentence numbers for ease of reference.

Title: How Can You Demonstrate the Water Cycle?

This title is interesting in that it tells the students that this is a modeling activity, as keyed by the word *demonstrate* and suggests that the target topic of the demonstration is the water cycle. In other words, after assembling and observing the model that is meant to be an analogy of the water cycle, the student is expected to have more knowledge about the water cycle.

The prototypic way for using analogy in instruction is to use the familiar, and often less complex idea, the vehicle, as an aid in understanding the new idea, the topic. That is, in this case, something about manipulating the flask, tubing, hot plate, water vapor, and ice--all rather common objects--will lead to a better understanding of the water cycle.

As the activity unfolds, however, one is not certain which is the topic of this activity--the water cycle or the processes involving the flask and beaker. Finally, we concluded that the main focus of the activity was to explain how the vehicle works, rather than how the target, topic, or phenomena work. That is, knowing how the water cycle works was more useful in answering questions found in the activity about the flasks, beakers, tubing, and ice, than was knowledge about the flasks, beakers, etc. in answering questions about the water cycle. We refer back to this problem later in the discussion.

Materials: table salt, water, beakers (2), flask, 1-hole stopper, rubber tubing, hot plate, cardboard, ice, shallow pan, glass tubing, glycerine, towel

While most of the materials needed to complete this activity were listed, we found that we also needed scissors, a stirring rod, scales, and a tasting rod. The most disconcerting aspect of this materials list is that it is not very functional. Notice that there is no description of the amount or size of any of the equipment. Consequently, we had to refer back and forth from the diagram to the instructions, carefully attending to sizes, in order to collect a functional set of materials. As a result, we spent about 40 minutes gathering equipment in a science laboratory that was well equipped, when the job should have taken a few minutes.

Typically, assumptions are made about what is usually available in an elementary or middle school classroom. Without these assumptions, the extreme and absurd form of a complete materials list could be very long, perhaps endless, and include such materials as a table on which to set the hot plate, a room in which a table is located, electricity, and so on. There must be some balance between a sufficiently complete materials list and a complete, but endlessly absurd one.

One partial solution to this problem may lie in the Activity-Centered Program Guide, in which the equipment and supplies for all the activities listed in the textbook are described. For example, the Guide denotes that a 250 ml, Pyrex beaker is needed for the flask activity. We think that this description of materials is very useful, and we are not sure why it was not incorporated into the materials list in the students' textbook and the teacher's manual. In its present form, the list is very cumbersome to use.

1. Dissolve 14 g of table salt in a beaker containing 227 g of water.

Sentence 1 is reasonable in that it requires the student to place a small amount of salt in water. We think, however, that it could have been worded more precisely--see our suggestion in the recommendations section.

The tricky aspect of this step is the requirement to use a specific weight of salt when a balance or scales is not listed in the materials list. Also, the amount of required water is listed as a weight equivalent. To weigh 227 g of water is rather complicated in that the beaker has to be weighed first, the scale had to be set for the total weight (the weight of the beaker plus 227 g), and water has to be poured into the beaker until the scale balances this total weight. Perhaps precise amounts were not necessary for this activity, but the unusually and capriciously precise amount, 227 g, invited the inference that an exact amount was necessary. Otherwise, the instructions could have read, "dissolve about 15 g of salt in about 250 g of water."

If the students realized, however, that 1 g of tap water is roughly equivalent to 1 ml or 1 cc volume of water, then they could measure the 227 g of water in a graduated container. Incidentally, a graduated container was not on the materials list.

2. Carefully taste the solution.

Tasting solutions is a potentially unpleasant, if not dangerous, laboratory procedure. The wording of Sentence 2 reflects this notion by including the admonition to be careful, but what does it mean to be careful? Be careful . . . Not to spill the solution? Not to drink too much because the experiment won't work? Because doing so is potentially bad for one's health? We suspect that all of these are reasonable, but being told to be careful does not ensure that students will use the proper procedures. What are they likely to do? Probably stick their fingers in the solution and then lick them. Considering the number of creative places that a student's finger is likely to have been, this is not a great strategy. Consider, for example, the number of laboratory objects that a student's finger may have touched just

prior to the tasting: salt, water, scales, table, beaker, pencil, paper, rubber tubing, and all the other equipment in the materials list.

We were surprised that neither the textbook nor the Activity-Centered Program Guide included a set of tasting procedures. In fact, the Guide simply admonishes students, as part of the Student Safety Contract, "Never taste any chemical substance or draw poisonous materials into a glass tube with your mouth" (p. 32). This admonition seems inconsistent with the requirement in the flask activity to "taste the solution."

3. CAUTION: Be sure the glassware is clean.

The caution stated in Sentence 3 is related to the dangers of tasting unknown liquids. The sequencing of this step is unfortunate in that if Sentence 2 is performed before Sentence 3 is read, then truly the tasting could be dangerous. Perhaps, Sentence 1 should be: "Thoroughly wash with detergent and hot water all glassware and tubing used in the activity."

4. Pour the solution into a flask.

Sentence 4 should not be a problem unless the flask is not big enough to hold all the salt solution. Even if this step does not go smoothly, however, spilled salt water is only mildly disruptive in a classroom.

5. Place the flask on a hot plate.

Sentence 5 is also rather easy, but one wonders why the flask was placed on the hot plate before the stopper and tubing were assembled. When we tried this, we observed that the flask was precariously perched on top of a slippery hot plate while stoppers and tubes were being attached to it. We recommend waiting until all the assembling has been completed before setting the flask and the tubing on the hot plate.

6. Insert a small piece of glass tubing through a one-hole rubber stopper.

7. CAUTION: Use glycerine and a towel to insert the tubing.

It is extremely important that the students realize that Sentences 6 and 7 go together. The first author of this report has a portrait of scars on his hands caused by glass tubes that broke while he was trying to insert them into old, hard-rubber stoppers. However, students may not know what glycerine is, how it should be used, and what the towel has to do with the activity--perhaps, to mop up blood!

The Activity-Centered Program Guide gives the following information about the procedures in Sentence 7.

> Place a drop of glycerol on the end of the tubing or thermometer. Glycerol acts as a lubricant. Wrap the glass tubing and the stopper in a cloth towel. Then gently push the tubing through the stopper with a twisting motion. Never hold the tubing or stopper in such a way that the end of the tubing is pressing against the palm of your hand. If the tubing breaks, it could easily injure your hand.

These procedures seem to be reasonable and effective, but they do not appear in the students' textbook. Also, note that these instructions refer to the product called *glycerol*. In the materials list *glycerine* was specified. Is it safe to assume that all teachers know that these are different names for the same product?

We found that it was easy to get glycerine (an oily, slippery liquid) inside the glass tube and rather difficult to remove it. Because this activity involved tasting procedures, we were not sure about the importance of keeping the glycerine on the outside of the glass tube, what to do when it got inside the glass tube, and what would happen if it were tasted.

8. Insert the stopper into the flask.

9. Make sure the glass tubing is above the surface of the solution.

10. Connect a length of rubber tubing to the glass tubing.

11. See Figure 10-2.

These steps went smoothly for us. Although they were more easily performed when the flask was sitting on a flat surface than on top of the hot plate. Also, we think that Sentence 9 should be labeled as a caution since the consequences of placing the glass tubing below the surface of the solution are rather dire. That is, the increased pressure caused by the trapped steam could blow the stopper off the flask, and hot water could be explosively forced through the tubing! More generally, we think that the explanations of cautions are important and should be presented.

12. Insert the free end of the rubber tubing through a hole in a small piece of cardboard.

This is a rather straightforward step, although the size of the hole in the cardboard is critical. The hole should be large enough to allow the rubber tube to slide through, but not large enough to allow ample steam to escape later in the activity.

13. Be sure to keep the tubing away from the burner.

Here we have another caution not labeled as such. Also, this caution is more appropriate to Sentence 17 (when the student supposedly turns on the hot plate) and should be located closer to it.

14. Place the cardboard over a beaker.

15. Add weight to the cardboard to hold it in place.

16. Set the beaker in a shallow pan filled with ice.

These steps are straightforward although the weight required in Sentence 15 is neither in the materials list nor shown in the diagram, nor is the student given the measure of the weight. Our experience showed that the cardboard became very soggy as the activity progressed, too much weight could cause the cardboard to sag, and the weight could tumble into the beaker of condensed water. Also, we think that procedures would be smoother if the beaker were placed in the shallow pan BEFORE the ice was added. Sentence 16 suggests that the reverse order be used.

17. Bring the solution to a boil.

Sentence 17 is a subroutine that most students are likely to know how to perform, although it requires turning on and adjusting the heat of a hot plate. We found that it took 8 minutes before the water started to boil, and an additional 28 minutes before almost all of the solution boiled away (Sentence 20). It seems important that students be told to give enough heat to the solution so that it will boil rapidly or else the activity will drag on too long. However, there are complications created by allowing the water to boil too rapidly (see Sentences 25 and 26).

18. What happens in the tube?

Sentence 18 contains the first observation that students are asked to make. The question in the sentence does not specify which tube is the object of the inquiry: the glass one, or the rubber one. We speculate that because the inside of the rubber tube cannot be seen, it must be the glass one. The glass tube was rather short, however, and there was not much to look at. Finally, the sentence is not clear about whether the students are supposed to record these observations or simply to make and remember them. The Activity-Centered Program Guide states that "students should keep records of their work in notebooks in a format that allows for easy review and checking. An outline can help students organize information. A recommended outline has the following headings: name; date; activity; title; data; observations; questions and conclusions." We are not convinced that this technique of recording observations is well suited for this activity, even if the teacher tells the students about the outline format.

Actually, when the water first started to boil, droplets formed inside the glass tube and ran back into the flask. Then, as the boiling became more intense, the tube cleared and there was nothing visible in the tube because steam is invisible. It became very, very hot; in fact, the entire apparatus (except the ice tray) became very hot.

19. What happens in the beaker?

In answer to the question posed in Sentence 19, we found that water drops fell from the end of the rubber hose into the bottom of the beaker. Later, the air inside the beaker became foggy. Eventually water droplets formed on the sides of the beaker and ran to the bottom. Gradually, the beakers began to fill with hot water, which was cooled by the ice. This series of observations should be easy for the student to make, although the step does not make it clear what should be done with this knowledge--record, remember, or forget it.

20. Continue the boiling until the solution is almost, but not quite boiled away.

21. Then discontinue heating.

These sentences are rather clear, although it would have been more helpful to students if Sentence 21 had read, "Discontinue heating when about 1 cm [or some other reasonable and arbitrary amount] is left."

22. Taste the water in the beaker.

To complete Sentence 22, we had to remove the rubber tube, weight (rock), and soggy cardboard before we could gain access to the beaker. This step also should have included a caution because the tube and cardboard were hot. Students should have been told to wait until the apparatus cooled before handling the tubing. However, this waiting period will make an excessively long experiment last even longer.

Proper tasting procedures should to be exercised here as in Sentence 2 because, if the tubing and glassware are not clean, the student may taste some nasty stuff.

23. Is it salty?

24. What remains in the flask?

The questions in these sentences also require students to make observations. Because we started with "unclean" equipment, we were not foolhardy enough to taste the water. Possibly, however, the water would have tasted salty! If the water in the flask were boiled rapidly, some of the salt spray could have landed on the tube and been transported to the condensation area. We did not attempt to determine

if this actually occurred. The remains in the flask were water and a cloudy film around the sides of the flask.

25. Is the combined water in the flask and in the beaker the same volume you placed in the flask at the beginning?

26. Explain.

To answer the question in Sentence 25, the student had to measure the amount of water remaining in the flask and the beaker. Notice that the question asked for the *volume* of water, rather than the *weight* as specified in Sentence 1. We weighed the water and found that while we started with 227 g, we could only account for 147 g. Therefore, about 80 g were missing. The teachers' manual said that the volume of the remaining water should be approximately 227 cc. The explanation for the large water loss is that the water was boiling rapidly, causing steam to fill the beaker. The steam escaped from the beaker into the air, the cardboard, and the rock. (Remember that the water boiled 28 minutes.) If the activity were done in such a way that all (or most) of the water could be collected, several procedures would have to be changed. First, the water would have to be boiled much slower so that the steam could condense in the beaker rather than escaping into the laboratory. Also, all the connections would have to be tightened, especially where the glass tube fits through the cardboard. Thus, we think the answer given in the teacher's manual is unrealistic and possibly misleading.

27. How is this activity like the water cycle? (The keyed answer in the teacher's manual to this questions is: "Water is evaporated and then condensed as it is in the water cycle.")

Obviously, the textbook authors were eager for the student to *infer* that the physical processes, evaporation and condensation, are common to the water cycle and to this activity. While it is rather obvious that these two processes are operating in the activity, it is not necessarily so with the water cycle. A student seldom sees evaporation in nature because it does not occur as a consequence of "boiling," the technique used in the activity, but rather as a consequence of slow, invisible water-to-vapor transformations at the surface of oceans (primarily), bogs, leaves, skin, and other moist surfaces. In fact, we are not sure that the likeness between "boiling" and evaporation is close enough to warrant its use in this model. When water boils, a small amount of it turns to water vapor at the "bottom" of the container and rises to the surface as a "bubble." It then escapes into the air. When water evaporates, the entire process takes place at the interface between water and air. We think that the process of boiling brings even less fidelity to the model.

Another serious problem is the fact that this activity does not portray a true "cycle." Note that the product of condensation is collected in a container and is not seen to participate in the "recycling" of water. To the student this must seem like a very linear process--the water starts at point A (the flask) and terminates at point B (the beaker). It is not clear to us how this activity could be modified so that the movement of water was cyclical. The challenge arises when one is trying to move the water from the beaker back into the flask, which would be a high-pressure steam chamber with a working model.

We think that the question in Sentence 27 could be improved if it asked the student to explain how this activity is NOT like the water cycle, as well, since many analogical vehicles have more dissimilarities than similarities to their target. Failure to adequately present dissimilarities while using models, simulation, and analogies during instruction is common and results in "seduction" (West, Farmer, & Wolff, 1991). We speculate that failure to recognize the dissimilarities in this activity might help students create or foster some of the following misconceptions:

a. That water can only evaporate if it is boiling.

b. That while the sun is the main source of heat for the earth's water cycle, the heat in the earth is what REALLY boils the water and causes it to evaporate. After all, how many people have ever seen the sun boil water?

c. That ice is required to condense water. Therefore, water can only condense over the earth's poles!

d. That only salt water can evaporate.

28. What is the heat source for the Earth's water cycle? The keyed answer in the teacher's manual is: "The sun is the main source of heat for the earth's water cycle."

We are not sure why this question is included unless the authors thought that the students might not see that the sun, rather than a giant hot plate, was the major heat source in the water cycle.

A summary of the critique of the flask activity can be found in Figures 1 and 2.

Critique of the Aquarium Activity

The aquarium activity was found in a fourth-grade textbook (Trowbridge, Sund, Adams, Hackett, & Moyer, 1983) and contains about 170 words. It has a title (or purpose), a list of materials, a set of procedural steps that could be executed, and questions (either inserted in the procedural steps or in a separate section at the end of the text). Also, it has a diagram showing how the equipment should be assembled.

Title: Using Solar Energy to Clean Water

This title indicates that the main idea of this activity is related to a purpose, namely, to produce clean water. The notion of water cycle is not central to the purpose, although as is clear below, the same mechanics that drive the water cycle are those that "clean" the water.

What to use: muddy water, large dishpan, metric ruler, 2 small rocks, small glass jar (must be shorter than the height of the dishpan), plastic wrap, and masking tape

The materials list is complete, although it doesn't include the sizes of most of the materials. Additional descriptions such as the amount of muddy water, the capacity of the dishpan, the comparative size of the rocks, and the type of plastic wrap would have been very helpful to the experimenters. Although we were working in a rather well-equipped science education laboratory, we spent about 30 minutes locating appropriate equipment and exchanging other equipment that wouldn't work.

What to do:

1. Put muddy water into the dishpan until the water is three centimeters deep.

This step went smoothly, although we found that walking to a sunny (hopefully) window ledge, as we were required to do later, with a large dishpan of muddy water must be done very carefully. It would have been helpful if the instructions had included something about the problems of transporting the pan of water. In most classrooms it would be best to mix the soil and water in a container less prone to spillage and pour the suspension into the wide pan.

2. Put a rock inside the jar. Place the jar in the middle of the dishpan.

Here we have the criterion for the size of one of the rocks--that it must be able to fit in the small glass jar but be heavy enough to keep the jar from floating. Nothing about the shape of the rock is mentioned, although a regularly shaped (cube or cylinder) weight would be more appropriate because the shape of the rock or other characteristics such as porosity could affect later critical measurements, as in Sentence 6.

3. Cover the dishpan with plastic wrap. Pull it tight. Tape the edges of the wrap to the sides of the dishpan.

This step does not indicate that the plastic wrap has to be clear. Black mylar, for example, would not be suitable. The commercial product, Saran Wrap, worked for us, but created some problems as discussed in Sentence 7.

4. Put a rock on the plastic wrap right above the jar. Do not let the rock or the plastic touch the jar.

Here is the criterion for size of the second rock, that is, it must not be so heavy that it caves the plastic wrap. The materials list could have specified that each of the two rocks be about the size of a large marble, for example.

5. Place the dishpan in a sunny place for one day.

We ran into trouble with this step because we did not do the experiment on a sunny day, but we did set the dishpan on a window ledge on which the sun would normally shine brightly. Our window had an eastern exposure that eventually became sunny. However, some classrooms face north and seldom have much direct exposure to the sun.

6. Early the next morning, remove the rock and the plastic wrap. Measure the depth of the water in the jar. Record your observations in the chart.

The terminology gets a bit confusing in these sentences. The student is told to check the water level in the jar early the next morning. The traditional time to have science in elementary classrooms, however, is in the afternoon, and if it is really important to wait a full 24 hours, early morning is inappropriate.

More important, however, is that we found that it was 3 days before there was enough water in the small glass jar to get any kind of a measurement! After six days, in fact, there was about 1 cm of water. We even placed the dishpan on a radiator vent (we did the experiment in the winter), but still in the direct sun to maximize the evaporation.

The students were told to record their measurements in the table reproduced below.

Day	1	2	3
Depth of water in jar			

7. Replace the plastic wrap and the rock. Repeat Step 6 for two more sunny days. Replace the plastic wrap and the rock after each measurement.

Unwrapping and rewrapping the plastic wrap was nontrivial. The plastic wrap was always wet from the moisture that condensed on the underside. When the wrap was removed, many other things became wet. The masking tape was no longer very sticky and had to be replaced. In addition, the Saran Wrap seemed to be promoting the beading of condensed water, which impeded the flow of water down the underside of the sheet into the glass jar. So, we experimented with another type of plastic wrap, one that did not "cling" as well as Saran Wrap. The water then seemed to bead less and flow more.

Unwrapping and rewrapping the plastic also inherently fouled the experiment. Because the wrap was wet from the condensation, some water was lost for the subsequent measures.

8. At the end of the activity, measure the depth of the muddy water. Record your results here.

Our experience showed that 3 days was not nearly long enough to get enough water to measure. Perhaps, after a week or two, there would have been enough. Also, we do not understand why the results would be written "here," rather than on the chart provided.

The following questions were listed in a section entitled *What did you learn?*

1. How does the water collected in the jar compare with the water in the dishpan? [Keyed answer: The water in the jar is clear, not muddy like the water in the dishpan.]

Interestingly enough, the keyed answer as given above was not very apparent to us when we performed the activity. In fact, there was not much difference in the appearance of the water in the jar and the water in the pan! This occurred because the dirt settled to the bottom of the "undisturbed" dishpan and the water looked very clear--just like that in the glass jar.

Perhaps this section should have included more questions about what happened to the dirt in the water. And, why didn't it move with the water from the pan? These probes might have helped the students understand the mechanics of the water cycle and how they are related to the process of cleaning water.

2. On which day did the most water collect? Explain. [Keyed answer: The most water will probably be collected on the warmest, sunniest day because evaporation will be greatest then.]

We did not collect enough water on any one day to note any differences. Even if we had been collecting a reasonable amount of water, such as a half centimeter per day, we would not have been able to answer this question very confidently because the rock we were using to weigh the jar down (so it would not float) was very irregularly shaped and quite porous. Thus the variations of our readings from day to day might have had little to do with the evaporation rate and much to do with the properties of the rock!

3. From where did the water in the jar come? How do you know? [Keyed answer: Water from the dishpan evaporated and then condensed on the plastic wrap. The rock caused the condensed water to collect and drop into the jar.]

In this keyed answer we have a two-sentence explanation of the water cycle using the technical process terms--evaporate and condense--to carry most of the explanatory load of how to "clean water." We think that this explanation is rather meager and insufficient.

The role of the rock as claimed in the keyed answer is interesting in that it seems to be a driving force in this process! "The rock caused the condensed water to collect and drop." Which rock--the one in

the jar or the one on the plastic? In either case, the rocks (or more appropriately, weights) should be thought of as inert variables in this water cycle model and not causal forces!

While the aquarium activity does not really solve the mystery of how one can use the sun's energy to "clean water," it does offer a model of the water cycle with somewhat more fidelity than the flask activity. However, the aquarium activity suffers from the same, serious fidelity problem as the flask problem--that is, the process is not cyclical but linear. The water evaporates from the bottom of the aquarium and ends up in the small jar. The model could be improved by using a tiny collection jar that would fill and overflow into the larger pool of water in the bottom of the aquarium. Thus, the water could be seen to move from the bottom of the aquarium, to the plastic wrap, into the collection jar and back into the bottom of the aquarium--a complete cycle.

Results of the Critique Analyses Using a Categorical Framework

We summarized our impressions of these activities by incorporating some of them into a categorical frame (see Figures 1 and 2), based on framing techniques discussed by West, Farmer, and Wolff (1991).

[Insert Figures 1 and 2 about here.]

Column A - Complete?

In this column, we give our assessment of how complete the various characteristics of the activity (materials list and procedural steps, for example) are. We considered whether all, or most, aspects were covered, without much focus on the quality of the characteristics. For example, we rated a set of procedural steps as being complete if all the essential steps were included, even though they may have been worded in a clumsy way or the sequence of steps was inadequate.

How Complete Were the Activities?

Our analysis indicated that neither of the activities was complete. For examples, the questions in both activities were incomplete, and the materials list in the flask model was incomplete.

Column B - Functional?

In this column, we give our assessment of whether each of the several activity characteristics would work. In arriving at this assessment we considered the quality of the written document as well as the integrity of the science.

One problem of special attention was the sequencing of ideas as represented in the procedural steps of the activity. Did Step b naturally follow from Step a? Was Step c really necessary? Should there have been a Step b' to help the transition between Steps b and c? Were Steps a and c redundant? Was the syntax of Step a clumsy or confusing? If the flow of ideas was out of sequence to the point that the activity would not work, we rated that characteristic as nonfunctional.

Likewise, if the questions in the activity did not direct the student in a pattern of thinking that was consistent with the goal of the activity, the questions were rated as nonfunctional.

How Functional Were the Activities?

Our analysis indicated that the materials list in the flask model activity was not a functional one. Too much equipment was missing, and if the teacher had only assembled what was listed, the activity would have been a failure. Also, the questions were so unrelated to the stated purpose of the activity, that to answer them would not be very helpful--perhaps even misleading. While we thought that the procedural

steps were rather complete, we were concerned that some of them were dangerous. For this reason we gave a qualified "yes" to the functional question.

The aquarium model appeared to us to be functional in virtually all aspects. Our one main reservation was that the questions were rather poorly worded.

Column C - Use of Words and Concepts

We also considered the use of vocabulary. We were particularly interested in how and when scientific/technical words and phrases were used in the prose. We assumed that it would be difficult (and unwise) to direct students through science activities without the use of technical words, such as *oceanography, flask* and *glycerine*. However, we were also interested in determining if nonscientific words were used in ways that were perhaps, too difficult, novel, out of context, or so simplistic and imprecise that they were misleading.

The Use of Words and Concepts

We found that both activities used words and referred to concepts that the students would be likely to understand.

Column D - Use of Commands and Subroutines

Also under the general topic of vocabulary, we looked at word clusters that we termed, *implicit commands and subroutines*. One type of implicit commands and subroutines was found in the materials list. There, we reasoned, that each entry was an abbreviated form of a command. For example, when the materials list included "muddy water," it probably meant to the teacher, "mix some dirt with some tap water and stir." To the student it probably meant, "Go to the table where the science activity equipment is usually found and pour some muddy water in a little jar." We paid special attention to the size, shape, color, and amount of each material. Our experience taught us that these were very important aspects.

A subroutine is a label that refers to a set of subsumed, and generally not written or spoken, implicit procedures. For example, "Cover the dishpan with plastic wrap," is a procedure taken from one of the activities. The action word, *cover*, refers to other procedures, which in this case are implicit. These implicit procedures are, roughly, (a) Tear off about 20 inches of plastic wrap. (b) Stretch it over the top of the container so that it is smooth and completely covers the top.

In turn, the word *tear* can be thought of as a subroutine and refers to other procedures: (a) Grasp the box of plastic wrap in one hand and the loose end of the roll in the other; (b) Pull the loose end of plastic wrap until the desired amount has been unrolled; (c) Hold the box firmly and pull the plastic wrap against the "teeth" in the box so that the plastic wrap starts to tear; (d) Continue tearing the plastic wrap across the entire sheet; (e) If (when) the plastic wrap becomes wrinkled and folds back on itself, carefully locate the corners and edges of the plastic wrap and pull them back into place. . . etc.

When designing and writing science activities, the author must decide which procedures must be explicit and which can be left tacit or implicit as a subroutine. For example, students in the sixth grade are likely to know what it means to "cover the dish pan," but may not know what it means to "CAREFULLY taste the solution." As we examined the text we tried to locate those commands and subroutines that many, if not most students, would not know how to perform.

Our caveat here is similar to our earlier caveat about adequacy of materials list. Just as some materials may be assumed to be available, some subroutines may be left unstated. Otherwise a list of procedures, complete with all subroutines, probably becomes infinitely long and extremely tedious. For example,

in the case of *tear* above, the subroutine began with *grasp*. *Grasp* itself could be analyzed as a series of moves comprising yet another subroutine. With both materials and subroutines the relative extensiveness is a matter not to be taken lightly.

The Use of Commands and Subroutines

We thought that the flask activity included some procedural steps that would likely confuse the students and might create situations that would be dangerous. The aquarium activity was much less complicated and had no serious subroutine problems.

Column E - Logistics and Dangers

One logistical aspect is time. How much time is required from the teacher and the students? Could it be completed at one sitting, or did it require time over several days or weeks?

Likewise, the organization of students, space, and equipment was considered. Were students expected to work individually, in pairs, in groups or as an intact class? Did students need special work stations with wet sinks and durable surface areas, or would a typical classroom table or desk top be adequate?

Finally, were there dangerous aspects to the activity? How likely were the students to get hurt? Or to damage property? Could safer procedures have been used?

Logistics and Dangers in the Activities

The flask activity has reasonable time requirements that should fit into most classroom routines, but should have a work surface which can withstand heat and water. In contrast with the aquarium activity, this one includes dangerous procedures, such as handling hot equipment, tubing steam and tasting liquids. The aquarium activity has reasonable time and space requirements that should fit into most classroom routines. The activity does not require procedures that are dangerous.

Column F (the first column in Figure 2) - Specific Facts That Were Observed

Observed declarative knowledge is the set of propositions observed and, perhaps, learned as a consequence of performing a specific science activity. For example, students might learn that moisture forms on the underside of the plastic wrap and clusters into droplets, that 80 g of water "disappeared" during the course of the flask activity, that 1 mm of water was collected in the bottom of the jar with the rock in it...etc. These are observed science facts, but are usually unique to the particular circumstances observed in the activity.

In these two activities, *what observational declarative knowledge was required and likely to be learned?* In the flask activity, there was a wide variety of observations that could be made which included tasting, feeling, measuring, timing, and seeing. The same can be said of the aquarium activity although it did not offer quite the same large array of possibilities--it is a less dynamic activity.

Column G - Principles Needed to Explain the Observations

The declarative knowledge of principles is more general than observational declarative knowledge. The knowledge principles can be thought of as an attempt to interpret or comprehend observational knowledge by comparing it with a "private theory of the nature of reality" (Rumelhart, 1980). Within this framework, comprehension or learning is thought of as the instantiation of one's theoretical knowledge (schemata, in Rumelhart's terminology) and that learning occurs when one feels that one's theoretical knowledge fits the observational knowledge that one is attempting to interpret. It appears

to us, that science activities are directed at the business of having students make observations and then determine how well they comprehend those observations by applying a model or a theory.

When reasoning that a student's understanding of observations made is dependent on the student's theoretical knowledge, the problem of which theoretical knowledge to give to a student is perhaps one of the most perplexing of problems for science curriculum developers and teachers. To illustrate this problem we developed three explanations of the water cycle based on the aquarium activity.

The *level one explanation* introduces the technical terms, *evaporation* and *condensation*, and their definitions which carry the bulk of the explanatory load. The explanation goes like this:

> The liquid water in the bottom of the dishpan changes into a gas, called water vapor. This process is called *evaporation*. The water vapor travels upwards until it comes in contact with the plastic sheet. There, the water vapor turns back into drops of liquid water. This process is called *condensation*. After many drops of water have collected on the underside of the plastic sheet, they run down the underside and drip into the jar.

The *second level of explanation* is an extension of level one but includes the influence of heat on the evaporation and condensation processes:

> Energy from the sun heats the water in the bottom of the dishpan and the air above it. This heating causes the water in the bottom of the dishpan to *evaporate*. When water evaporates it changes from liquid water to a gas called water vapor. Some of the water vapor travels upwards until it hits the plastic sheet. When the plastic sheet is cooler than the air inside the covered dishpan, the water vapor *condenses*. When water vapor condenses, it changes from a gas to drops of liquid water. After many drops of water have collected on the underside of the plastic sheet they run down and drip into the jar.

The *third level* of explanation builds on the previous level but introduces the theoretical notions of molecular motion and gravity:

> Energy from the sun heats the water in the bottom of the dishpan and the air above it. The sun's energy causes the water and air molecules to move much faster. When the water molecules move faster, more of them break away from each other and mix with the air molecules above the surface of the liquid water. This process is called *evaporation*. When water evaporates, it changes from liquid water to a gas called water vapor.
>
> Since the air molecules are also moving very fast they are able to bounce the water molecules around until some of them hit the plastic sheet. When the plastic sheet is cooler than the air inside the covered dishpan, the air and water molecules slow down. Then, more of them stop mixing with the air molecules and begin sticking together again to form water drops. This process of sticking together is called *condensation*. Therefore, when water vapor condenses, it changes from a gas to drops of liquid water. After many drops of water have collected on the underside of the plastic sheet they become so large that the force of gravity causes them to run down the plastic sheet toward the rock and drip into the jar.

It's clear that as the level of explanation becomes more complex: (a) the number of components in the explanation increases, (b) the explanation changes from one of definition to one of cause, and (c) the explanation becomes more dynamic and conditional. We suspect, then, that students who do not have

knowledge about molecular motion, for example, would not find the Level Three explanation very helpful.

What Principles Are Needed to Explain the Observations from These Activities?

Our analysis showed that a wide array of principles are needed to explain the observations in each activity. Those associated with the flask activity are more numerous and varied, however, than those with the acquarium activities.

Column H - Investigative Strategies

In this column, we recorded comments on the type of investigative strategy used in the activities because scientists, to a greater extent than experts in most other knowledge domains, typically consider the techniques, strategies, or methods of science to be central to it. Results of the methods--considered to be declarative knowledge in our categorization system--are much more likely in science than in other domains to be considered as secondary in significance. Thus, what we call in this paper investigative strategies are considered by experts in this knowledge domain to be extremely critical in the induction of elementary youth into science. Embedded in all of these are the usual observation/measurement considerations--which, when simply put, mean that scientific observations should be reliable, valid and replicable--but there are others. For example, scientists must sequence and anchor their observations and classifications (which also should be reliable, valid and replicable) according to some pattern or tradition. These traditions include experimental methods and model building. Each of these investigative strategies is represented extensively in the science activities found in elementary curriculum packages.

When experimental methods are employed, repeated observations are made when all the variables thought to affect this phenomenon, except one, are held constant, and that one is manipulated. The results of such a strategy allow the experimenter to make inferences about causes of the event being studied. An example of an experimental activity in the sixth-grade curriculum materials is one on the effects of disinfectants on the growth of bacteria. Slices of apple were treated with various kinds of disinfectants which were then exposed to the air for several hours. Another slice of apple was not treated with any type of disinfectant. Results from this activity are thought to help students make inferences about the relative effects of disinfectants on the growth of bacteria.

Another investigative strategy is *model building*. The rationale underpinning model building is that many events or objects are so complex, subtle, mammoth, minuscule and/or infrequent that they cannot be easily observed or manipulated. Examples include planetary motion, volcanic eruptions, molecular motion, the water cycle, and plate tectonic motion. In an attempt to better understand some aspects of them, a so-called model is constructed. For examples, a globe is a model of the earth, stick-together beads can be used to represent molecules, and plastic dishpans covered with plastic wrap can be used to approximate the environment in which the water cycle operates.

In These Activities, What Investigative Strategies Are Required and Likely to Be Learned?

The investigative strategy used in both of these activities was modeling. Somehow, setting up and observing the flask and aquarium activities were supposed to help students understand the water cycle. According to our analysis, each of the activities has fidelity problems, especially the flask model, to the point that the students are not very likely to be convinced that modeling is very helpful. In the literature on instructional uses of analogy, fidelity is, generally speaking, the match between the vehicle and topic. Similarly, in the simulation literature it is the match of characteristics of the model with the phenomenon being modelled.

Column I - Procedural Knowledge of Laboratory Skills

Laboratory procedures are those that are necessary to perform a science activity and are likely to be used again in future laboratory work. These include using a balance, operating a calculator, lighting a Bunsen burner, tasting a liquid, measuring dry chemicals, pouring liquids, and constructing charts.

What Laboratory Procedures Are Required and Likely to Be Learned from the Two Activities?

The flask activity required a much greater variety of laboratory procedures including weighing, measuring, recording, and tasting.

Column J - Procedural Knowledge of Other Applications

Certain other procedures can also be learned during the performance of a science activity that are not necessarily transferable to other laboratory settings, but may transfer to other work, living or play settings. Examples of some of these other procedures from the two water cycle activities include: unwinding, cutting and taping plastic wrap (the modern equivalent of the Gordian knot), and transporting liquids in a large flat container.

What Other Procedures Are Required and Likely to Be Learned from the Two Activities?

Actually neither of the activities required many additional procedures (i.e., those procedures not thought to be laboratory skills). The reason we include this category is that other activities we investigated included procedures which might fit in this category, such as peeling apples, planting seeds, and blowing up balloons.

Summary

We analyzed two typical science activities found in textbooks with an eye to the quality of the written text and the integrity of the science represented in the activity. Each activity was performed and critiqued from a number of perspectives. Our analyses found that both activities contained serious defects, perhaps functionally, procedurally, logically or in the modeling strategies used.

Recommendations

1. We strongly advocate that the use of science instruction, including hands-on activities, increase and become a mainstay in all classroom instructional programs. We think that when students are required to complete successfully a well-conceived activity, they gain a variety of knowledge that cannot be acquired elsewhere very easily. Unfortunately, our analyses in preparation for this project have led us to believe that the quality of most activities accessible to teachers is rather poor. It may be that some children's misconceptions are abetted by poorly conceived, designed, and executed activities.

2. We recommend that activities published for classroom use first be "field tested" with students in the intended age group. If pilot students had tried to follow the procedures in these activities as we did, we feel quite certain that many of the confusing, if not dangerous steps, activities, and associated procedures would have been detected and improved.

3. We recommend that teachers be given more information about all aspects of the activity, especially about the different types of knowledge that students are likely to need. Teachers should know what scientists, as well as students, think about all aspects of the activity. This recommendation is based on the premise that most teachers will not have the time to pilot every activity that they use in the classroom, and even if they could, their own single perspective would not be as rich as those of various scientists and students.

4. We recommend that, for the teacher's benefit, special emphasis in the teacher's manual be given to the type and importance of the investigative strategy being used in an activity. In our review of approximately 50 activities we did not find material accompanying any activity that required the students to mentally "step back" and take a "macro" view of the investigative strategy itself. We think that knowledge of the investigative strategy is, perhaps, the most important knowledge that a student could learn from a science activity; and, at the same time, the knowledge that most teachers are ill-prepared to discuss. This emphasis is consistent with the prime value that scientists place on their methods and their perspective that method is the essence of science.

5. We recommend that the procedural text be written clearly. Even when authors consider text to be clear it will often be confusing to a surprisingly large number of students. Most students are not taught to read procedural text and when asked to do so are often confused (Burnham & Anderson, 1991). Field testing (see Recommendation 2) should provide immense help in detecting confusing passages.

There are many aspects of preparing and presenting text that could be used to improve procedural text--these include page format, syntax, and vocabulary considerations. See Burnham and Anderson (1991) for a discussion of research on factors that affect the comprehension of procedural text. For example, the flask activity would have been clearer if the procedural steps were numbered and printed in larger font sizes. Also, we suspect that rewording some of the steps in ways illustrated below would have helped both activities:

a. *Dissolve* 14 g of table salt . . . .

a' Pour 227 g of water into a flask containing 14 g of salt. Stir the solution until the salt dissolves.

b. *Connect* a length of rubber tubing to the glass tubing.

b' Insert the end of the glass tube into the rubber tubing.

c. *Bring* the solution to a boil.

c' Turn the hot plate on and heat the water until it boils rapidly.

d. *Carefully taste* the solution.

d' Dip a clear glass rod into the solution. Remove the rod and gently shake any drops from the end of the rod. Touch the end of the rod to the tip of your tongue. After tasting, rinse the rod and your mouth with water.

6. We recommend that authors make the materials list more complete. We think that the materials list ought to be complete enough so that the teacher or student could use it without other aids to collect all needed materials for the activity. The most obvious problem with the materials lists is the omission of sizes and descriptions of equipment--a situation which could be easily remedied. It seems inconsiderate of the teachers' time not to make planning and organizing for an activity easier.

7. Finally we recommend that authors of science activities and teachers become familiar with the current literature on sound instructional uses of analogy (e.g., Spiro, Feltovich, Boulson, & Anderson, 1988; West, Farmer, & Wolff, 1991) and simulation (e.g., West, Snellen, Tong, & Murray, 1991). During this research we frequently encountered the fact that the activity was being used as a "model" (or "simulation") or as an analogy for the water cycle. Analogies and simulations can be powerful instructionally, or even scientifically, for they are strategies which are intrinsic to science; but, when used instructionally, authors and teachers must decide that the activity is either the model to be studied or

the phenomenon to be observed. The activity cannot, instructionally, be considered as simultaneously the simulation and the phenomenon itself, as was done. Nor can the activity be both the "topic" and the "vehicle" in an analogy, which was also done. Familiarity with this current literature should help teachers and authors avoid the confusions which arise from intellectual overextensions from models and vehicles to the phenomenon which is presumably the object of the activity.

On the other hand, we believe that there is a place in science education for "minds on" activities that are highly exploratory. It may even be desirable for some activities to be merely generally described so that creatively planning investigations and models toward the ends of exploration and explanation may be engendered. Among the activities we critiqued, however, we found little sense of these kinds of purposes.

These recommendations are not conceived within a perspective that science, even pre-secondary science, can or should be "cut and dried." We do, however, share a perspective that most pre-secondary science activities should be conceived and described in text sufficiently well enough so that teachers and students can follow procedures which are orderly, clear, and relatively complete, and actually can be performed--and will actually "work."

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Figure 1: Characteristics of the Activity

	A Complete?	B Functional?	C Use of words and concepts	D Use of commands and subroutines	E Logistics and dangers
Flask Model					
1. materials list	no	no, essentials were missing	appropriate and understandable	most are appropriate because the teacher gathers the materials	....about 1 hour to complete ...requires a work surface which could get wet and hot ...there are several dangerous procedures including handling hot equipment and tasting liquids.
2. procedural steps	yes	almost, but some were confusing and dangerous; the paragraph style was bad	minor problems but acceptable	some were confusing	
3. questions	no	no, unrelated to purpose	acceptable	acceptable	
4. diagrams	yes	yes	acceptable	acceptable	
Aquarium Model					
1. materials list	yes	yes	acceptable	acceptable	....about 1 hour to complete on day 1, and then about a week of short observations ...requires a work surface which could get wet ...there are no dangerous procedures.
2. procedural steps	yes	almost, although the cycle didn't work very fast	acceptable	acceptable	
3. questions	no	partially, the questions only dealt with part of the model and were worded poorly	acceptable	acceptable	
4. diagrams	yes	yes	acceptable	acceptable	

Figure 2: What is Likely to be Learned?

	F specific facts that were observed	G principles needed to explain the observations	H investigative strategies	I laboratory skills	J other applications
Flask Model	a. water in the flask tasted salty b. nothing seemed to be moving thru the glass tubes c. the tubes and flask got very hot d. some water vapor escaped around the cardboard e. a film was left on the flask after the water boiled away. f. water droplets formed on the walls of the beaker g. the ice melted h. cool water collected in the beaker i. it took about 28 minutes for the water to boil away j. water in beaker was not salty	a'. the salt was in solution b'. steam is invisible c'. water boils at a high temperature (100 C), a salt solution boils at an even higher temperature e'. salt does not evaporate, but is left behind f'. water vapor condenses into water droplets when it is cooled g'. heat from the water vapor melted the ice h'. gravity pulled the droplets into the bottom of the beaker i'. a lot of heat is required to make water boil j'. the salt stayed in the flask	...a modeling strategy is used but is not likely to be very effective since its fidelity is rather low.	...weighing solids and liquids ...determining the volume of solids and liquids ...assembling glass and rubber tubing and rubber stoppers. ...recording descriptive observations .. tasting liquids ...operating a heat source ...washing	
Aquarium Model	a. the water looked muddy when the activity started, but clear when it was over b. drops of water formed on the underside of the plastic wrap c. some drops slid down the plastic and dripped into the jar d. not very much water collected in the jar e. when Saran Wrap was used the drops just beaded up and would not run down toward the jar very easily	a'. the dirt particles were large enough to settle to the bottom and made the water look clear b'. water vapor condenses when it encounters a cooler surface c'. gravity pulled the drops "downhill" d'. the activity was done in the wintertime when there was not much sunshine. e'. water adheres better to some surfaces than to others	...even though modeling the water cycle is not the main purpose, it is likely to be a rather effective model since the fidelity is high, e.g., components in the activity are easy to match up with those in the water cycle--the ocean surface, sun, upper atmosphere, and precipitation can be identified in the aquarium	...determining the depth of liquid in a container ...organizing measurements in a table/chart ...transporting a dishpan containing muddy water	...dispensing and taping plastic wrap